Faculty of Technology, Design & Environment

Assessment cover

OXFORD BROOKES UNIVERSITY

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Module No:	ENGR7025	Module title:	Electric Vehicles

Assessment title:	Assignment 2 Mini Project: Cell Charge Balancing for Battery Management System

Due date and time:	28/04/2023 at 13:00

Estimated total time to be spent on assignment:	70 hours per student

LEARNING OUTCOMES

On successful completion of this module, students will be able to achieve the module following learning outcomes (LOs): *LO numbers and text copied and pasted from the module descriptor*
1) Appraise different electric vehicles architectures, evaluate and compare their performance.
2) Evaluate different types of electric machines for vehicle propulsion to recommend choices and assess associated energy recovery systems.
3) Analyse and assess performance of a range of energy storage systems, including associated safety and battery management systems.
4) Consider different controller and inverter types and evaluate their operation and suitability for automotive applications.
5) Assess different electronic sub-systems such as on-board communication and shutdown system required for safe operation of an electric vehicle.
6) Assess electrical energy provision, energy sources and electrical grid mix composition. Quantify different options using whole lifecycle assessment.

Engineering Council AHEP4 LOs assessed (from S1 2022-23) *LOs copied and pasted from the AHEP4 matrix*	
M1	Apply a comprehensive knowledge of mathematics, statistics, natural science and engineering principles to the solution of complex problems. Much of the knowledge will be at the forefront of the particular subject of study and informed by a critical awareness of new developments and the wider context of engineering
M2	Formulate and analyse complex problems to reach substantiated conclusions. This will involve evaluating available data using first principles of mathematics, statistics, natural science and engineering principles, and using engineering judgment to work with information that may be uncertain or incomplete, discussing the limitations of the techniques employed
M3	Select and apply appropriate computational and analytical techniques to model complex problems, discussing the limitations of the techniques employed
M4	Select and critically evaluate technical literature and other sources of information to solve complex problems
M5	Design solutions for complex problems that evidence some originality and meet a combination of societal, user, business and customer needs as appropriate. This will involve consideration of applicable health & safety, diversity, inclusion, cultural, societal, environmental and commercial matters, codes of practice and industry standards
M7	Evaluate the environmental and societal impact of solutions to complex problems (to include the entire life-cycle of a product or process) and minimise adverse impacts

Statement of Compliance ***(please tick to sign)***

☑ I declare that the work submitted is my own and that the work I submit is fully in accordance with the University regulations regarding assessments *(www.brookes.ac.uk/uniregulations/current)*

School of Engineering, Computing & Mathematics

Introduction

Electric and hybrid vehicles are considered potential replacement for the conventional IC engine vehicles to develop a clean, efficient and sustainable mobility for urban transportation. Rapid development has been made in this domain. Batteries are the main source energy and are critical component of the powertrain, responsible for storing and delivering power to the electric motor. At present, many different types of battery are considered as an option, including metal hydride, lead acid, lithium-ion, and others. Among these, lithium-ion batteries are commonly preferred because of their high energy density, low self-discharge rate and low maintenance advantages. However, if Li-ion batteries are used outside the safe working limits they are subjected to experience surge in temperature and voltage and can get damaged resulting in negative consequences of performance and safety of the battery as well as the overall operation of the vehicle. The batteries are subjected to experience frequent variation in their SoC due to the acceleration and regenerative patterns (Dange, et al., 2019)**.** This describes the need for a battery Management system. BMS constantly monitors multiple parameters of the battery pack such as charging and discharging of individual cells, and protects the battery unit from overcharging and over discharging in order to maintain the health of individual cells and entire battery pack. Apart from estimating State of Charge, the other objective of a BMS is to balance the individual cells, to monitor the overall thermal management, and provide a safe operation and increase the battery life expectancy. Since the battery pack is charged and discharged as a complete unit the individual cell temperature and their chemical characteristics cause capacity imbalance. (Dange, et al., 2019)

In the following part of the coursework, we have discussed about the cell balancing techniques and have simulated and discuss the issues associated with battery pack models without cell balancing circuit, and model using diodes for cell-balancing. Further a cell-balancing method is proposed and discussed in detail.

Cell Balancing

Cell balancing is a method that maintains an equal SOC across individual cell in the battery pack by monitoring and controlling them individually, this allows to reduce the stress on weaker cells which could cause early failure of the battery. The cell's in the battery pack are balanced when the individual cells are in fully charged state or discharged state. Cell balancing is commonly achieved using two techniques (Scott & Nork, n.d.)

a. Passive Balancing
b. Active Balancing

In passive cell balancing technique the excess charge of the fully charged cell is removed using bleed resistor to equalize cell voltages. Whereas in an active cell balancing technique a supplementary storage e.g. capacitors or inductors is used to redistribute charge between cells. (Jeon, et al., 2015)

Cell balancing is done to

- To maintain same SOC across different cells in the module
- Prevent the cells from overcharge & over discharge
- Improve the overall usable capacity of battery pack
- Ensure that the battery can achieve 100% SOC
- Improve coulombic efficiency of the cells and the battery pack.

Part A-Series capacitor behaving like re-chargeable batteries

In the following circuits, four capacitors are connected in series which represents/acts as rechargeable batteries. Both circuits include a resistor to limit the flow of current entering the main circuit and also consist 2 switches for charging and discharging condition. In circuit B, a pair of LED is connected in parallel across each capacitors which act as diodes used for cell balancing.

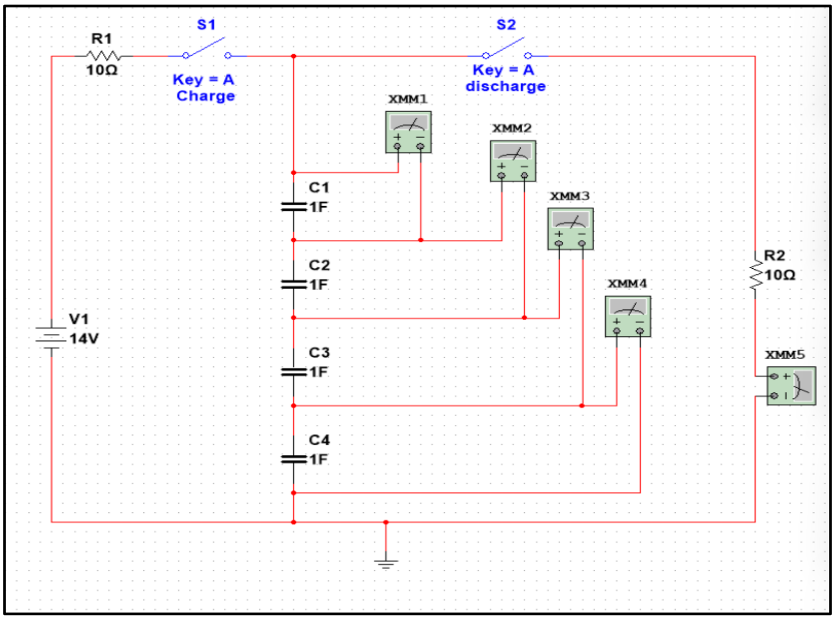


Figure 1 Circuit A

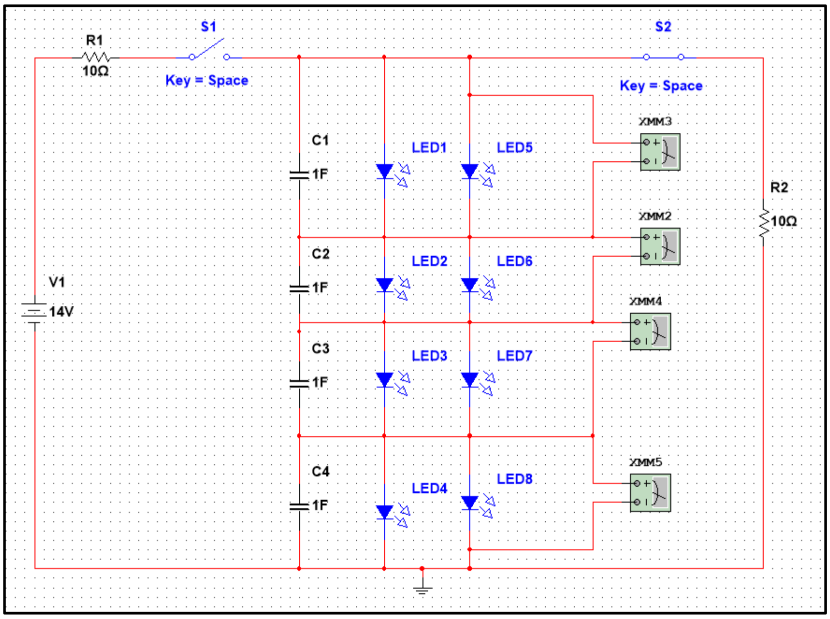


Figure 2 Circuit B

Observation

	Condition	Cell 1	Cell 2	Cell 3	Cell 4
		V	V	V	V
Circuit A	Max. Voltage across each cell if the Capacity is 1F	3.49	3.49	3.49	3.49
	Max Voltage across if the Capacity is 1F (except for C3 having 0.8F)	3.28	3.28	4.10	3.28
Circuit B	Max Voltage across each cell if the Capacity is 1F	1.96	1.96	1.96	1.96
	Max Voltage across if the Capacity is 1F (except for C3 having 0.8F)	1.96	1.96	1.96	1.96

Table 1 Maximum voltage observations across different circuit configuration

The voltage across each individual cell will depend on their individual voltage rating, State of Charge & State of Health. State of Health represents the condition of battery and total battery capacity available in comparison with nominal battery capacity in terms of percentage. Reduced battery capacity is a result of the battery ageing process, factors such as storage SOC, current rates, operating temperature, battery operating range, depth of discharge, operating duration, manufacturing flaws etc influence the ageing of the battery (Yang, et al., 2021). In this case the SoH can be related with the total capacitance. Due to reduced capacity, the ability of the cell to hold charge is limited, therefore, cell with lowest capacitance will reach the full limit well before other cell. The weaker cell with smaller cycle depth will thus limit the capacity of other cells in the battery pack (Seger, et al., 2022).The effect of cell imbalance results in reduced overall capacity and average life of the battery pack (Husain, 2010).

In actual practice a cell is never charged or discharged up to its extreme capacity.

Circuit A

Case 1: - Circuit with all cells(capacitor) having same capacity (i.e. 1F)

As each cell in the circuit have identical parameters i.e. in terms of total capacity, the voltage across them were observed to be the same at any given point of time.

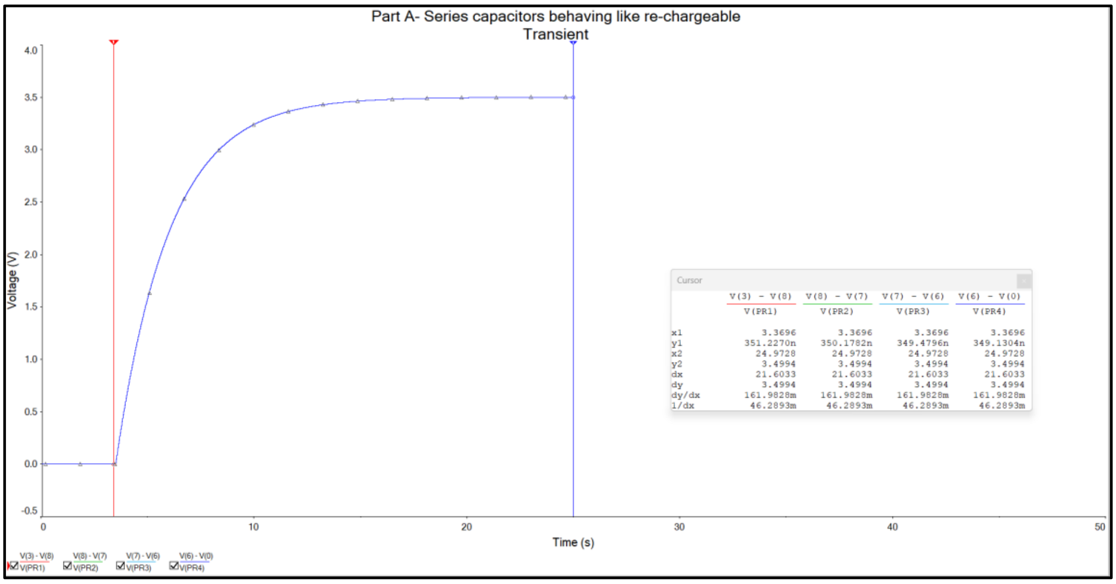


Figure 3 Maximum voltage for Circuit A when all the capacitors have capacitance 1F

The **Figure 3** shows the charging curve for Circuit A where a maximum voltage of 3.4994V was observed.

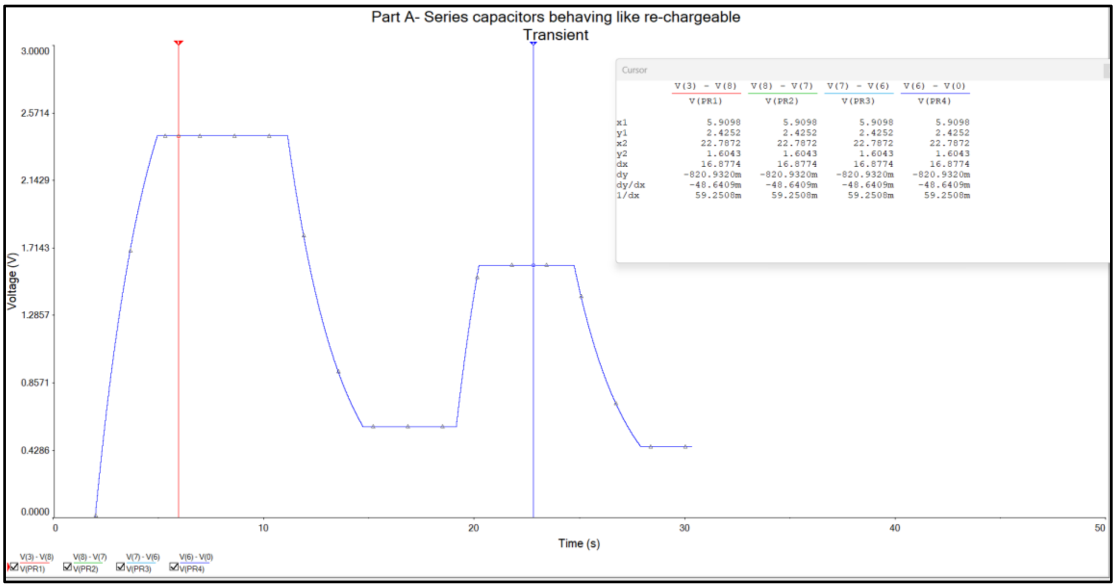


Figure 4 Charging and Discharging curve for Circuit A when all the capacitors have same capacitance 1F

The **Figure 4** shows the charging and discharging curve when each cell were charged for about 2.5V then both the switches were kept open then allowed to be discharged to approximately 0.4V and again charged to approx. 1.6V after which both the switches were left open and then discharged again. The charging and discharging pattern were observed to be same.

Case 2:- <u>Circuit with cell(capacitor) C3 having 0.8F capacitance</u>

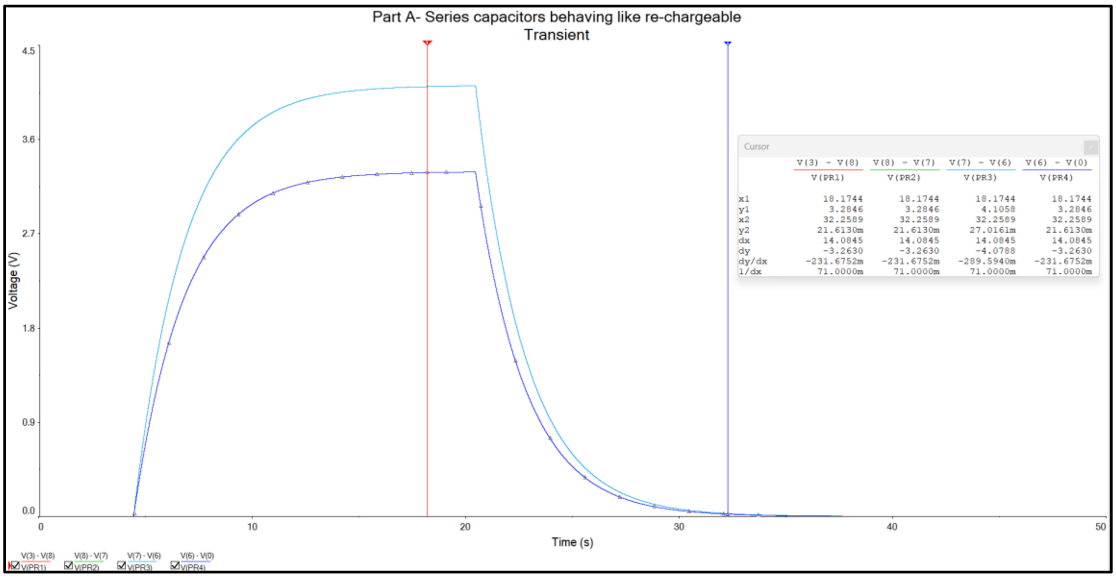


Figure 5 Maximum voltage for Circuit A when capacitor C3 is set to capacitance 0.8F

- Due to lower capacitance, C3 reaches its full charge capacity before other cells, after which it will stop accepting further charge while other cells still continue to get charged. Due to which the voltage of the cell continued to increase. As a result, we can observe the voltage across capacitor C3 to be on higher side in comparison to other three capacitor.
- Similarly, because of its lesser capacity, C3 discharges more quickly, causing its voltage to drop faster than others.

In both the preceding cases, since all the cell were charged to full capacity and there was no demand for power there was no change in voltage when both switches were open.

Circuit B

This circuit is an example of passive cell balancing technique where the current from the cell is drained out to balance the voltages of the cell, but the major limitation of this technique is the loss of energy and reduced use of the battery pack.

Case 1:- <u>Circuit with all cells(capacitor) having same capacitance (i.e. 1F)</u>

- The Voltage across all the capacitors remained same at any given point of time.

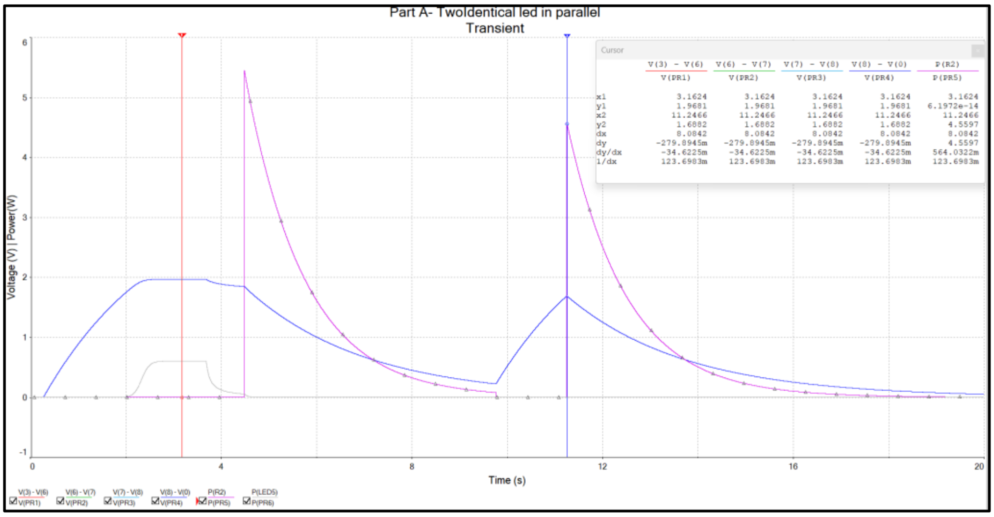


Figure 6 Charging and Discharging curve for Circuit B when all the capacitors have same capacitance 1F

Case Study 2: - <u>Circuit B with capacitor C3 with 0.8F capacitance</u>

- Since a cell balancing technique is being used the maximum voltage across each capacitor was the same. But capacitor C3 reached the peak voltage well before other cells but remained constant.
- The Charging and discharging rate of C3 was on higher side.
- Despite the cell balancing is used to balance the voltage across the cells during the charging state, the discharging capacity is limited by the cells with the lowest capacity. An over discharge of the weaker cell was observed.

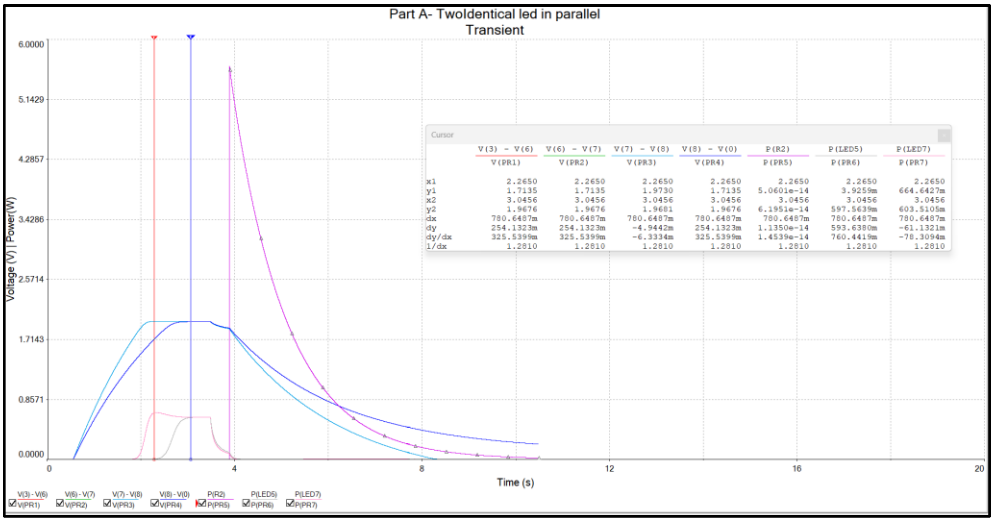


Figure 7 Charging and Discharging curve for Circuit B when capacitor C3 has a capacitance of 0.8F

The diodes(LEDs) connected across the cell will always draw current from the cell when the available voltage in them is above the operating voltage of the LEDs, this ensures that the charge during cell charging remains equalised. Due to this when both switches were kept open after achieving peak voltage, a drop in voltage was observed, but as soon as the voltage across the capacitors fall below the LED's operational voltage, there was no longer voltage drop observed and the voltage remained constant. In this circuit cell balancing was achieved using a diode but it resulted in voltage drop across cell, power loss, over discharge and reduced efficiency.

Part B-Design and Simulation of a Battery Management System

To overcome the limitations associated with cell balancing approach used in Part A an alternative option is proposed which focus on achieving efficient cell balance and automatic circuit protection for both charge and discharge condition.

The proposed design uses a combination of passive and active cell balancing technique where instead of bleeding the extra charge or transferring charge from one cell to other, a MOSFET is used as balancing switch to automatically bypass the fully charged cell to accomplish lossless cell balancing. In this method during charging state the cell with 100% SOC is isolated and bypassed after reaching set limit to avoid overcharging until other cells reach the same state. Similarly during discharge once the available charge in the cell reaches the lower limit, the cell is cut-off so that they are not completely drained off. (Musameh, et al., 2014)

This method allows to achieve cell balancing with better overall efficiency of the system and also minimising the power loss.

The proposed design has four working states

- Charging
- Discharging
- Suspended state after charging
- Suspended state after discharging

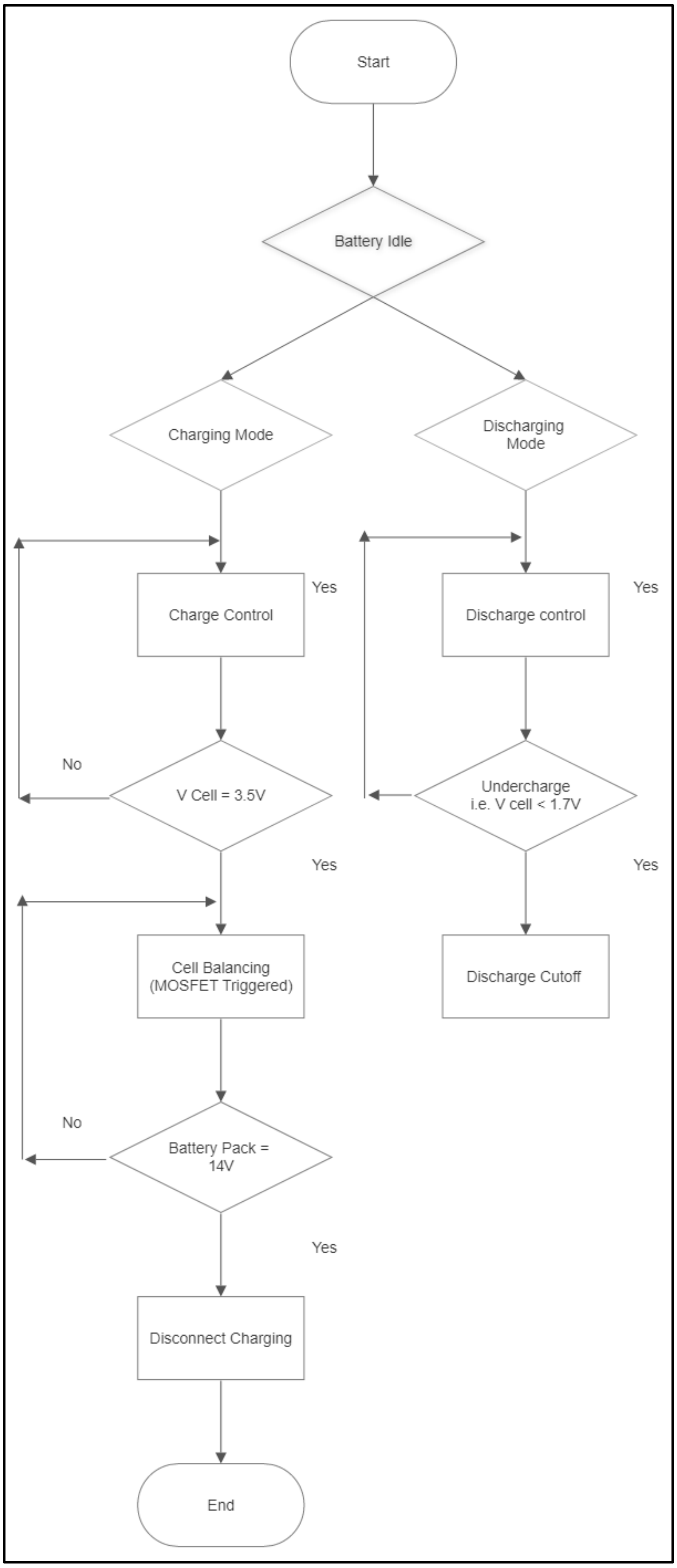


Figure 8 Flowchart describing the operating logic of the proposed design

Design

The following circuit is distributed in two half, one for charging and the other for discharging.

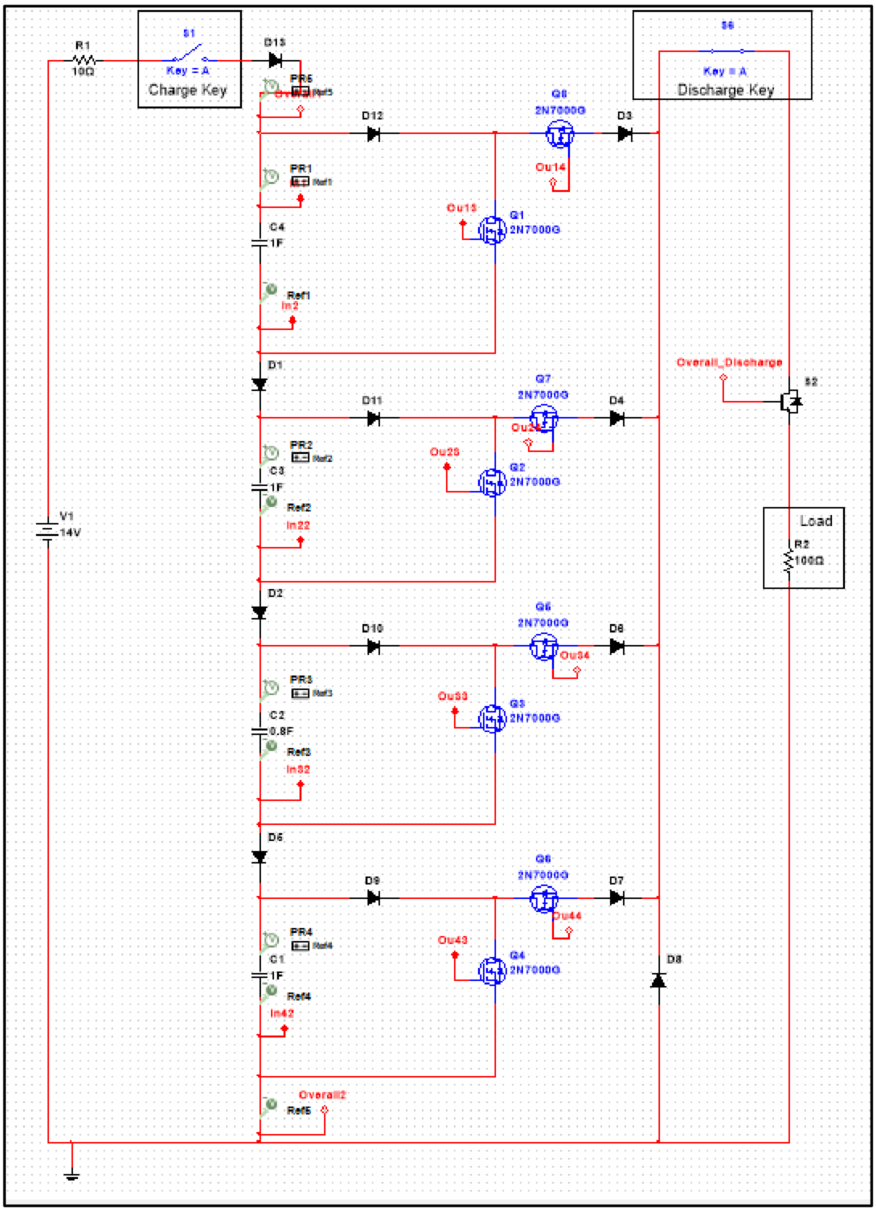


Figure 9 Proposed Cell balancing circuit

Firstly focusing on the charging side, a resistor is incorporated at the beginning just after the input source to control the current flow rate. A transistor diode is placed between the charging switch and the battery pack to cut-off the additional supply to the battery pack once it reaches the max voltage despite the state of charging switch. This allows to limit the excess flow of current after the desired limit enabling to achieve lossless balancing. Each cell in the battery pack is monitored individually so that once the threshold nominal voltage of a cell is achieved the MOSFETs are triggered and the cell is bypassed, this way overcharging of the cell can be avoided. A diode before each cell is used to oppose the flow of charge from one cell to other in reverse direction.

For monitoring and controlling the voltage of each cell individually a combination of difference amplifier and comparator amplifier is being used, a difference amplifier is used to measure the voltage across the cell and is fed as an input to the comparator amplifier which compares the voltage of the cell to the reference voltage. Once the voltage in the cell reaches the reference voltage the MOSFET is triggered this allows the current to bypass the cell.

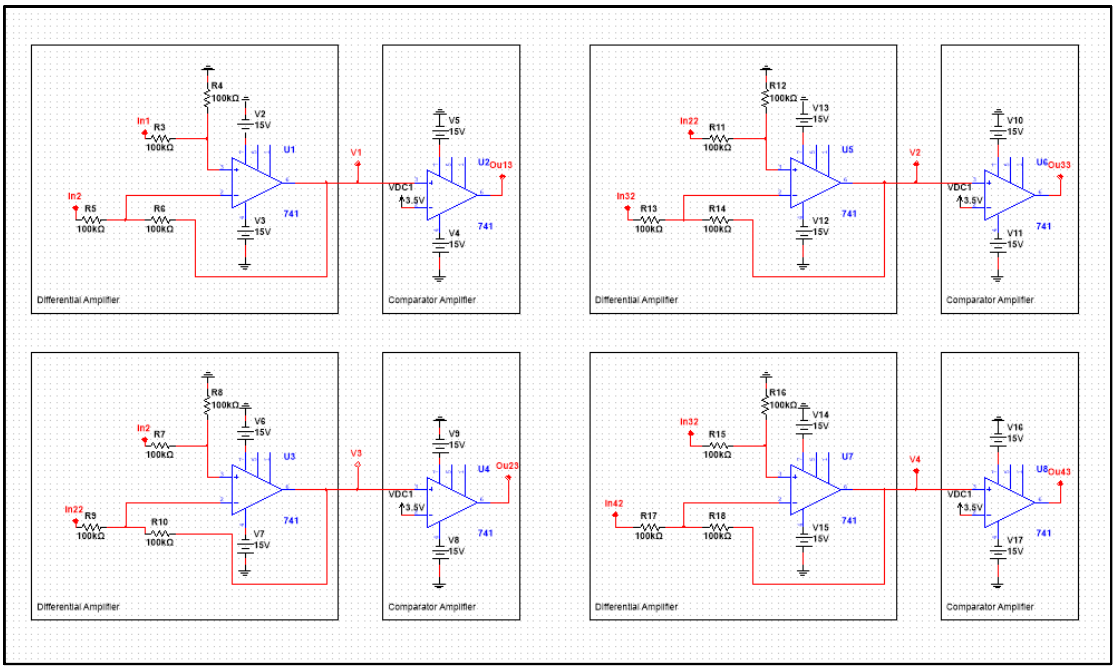
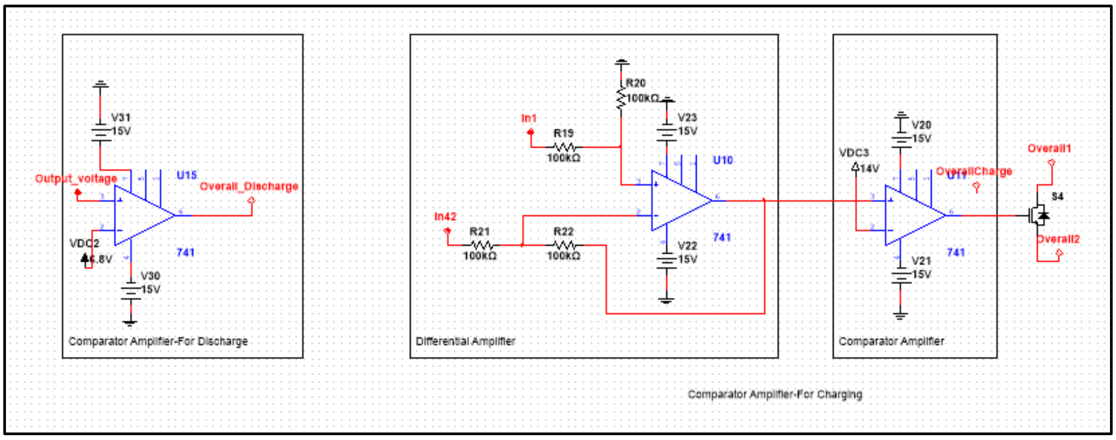


Figure 10 Controller circuit for triggering MOSFETS during charging condition to avoid over-charging of the cell



On the discharging side, each cell has MOSFETs connected across, which allow the flow of current during discharge only if the available charge in the cell is above the minimum limit. Once the cell is reduced to anything less than the discharge limit, the cell is isolated and will not be allowed further discharge to avoid over discharging of the cell. An additional transistor is used to control the discharging of the entire battery pack.

The amount of energy that can be stored in a battery cell is $E_{available} = qV$, which states that for cells connected in series, both charge and voltage must be balanced to maximize the output of the battery pack. (Husain, 2010),

Parameter	Value
Maximum Voltage	4 V
Nominal Voltage	3.5 V
Discharge Voltage	1.7 V

Table 2 Battery specification

Results

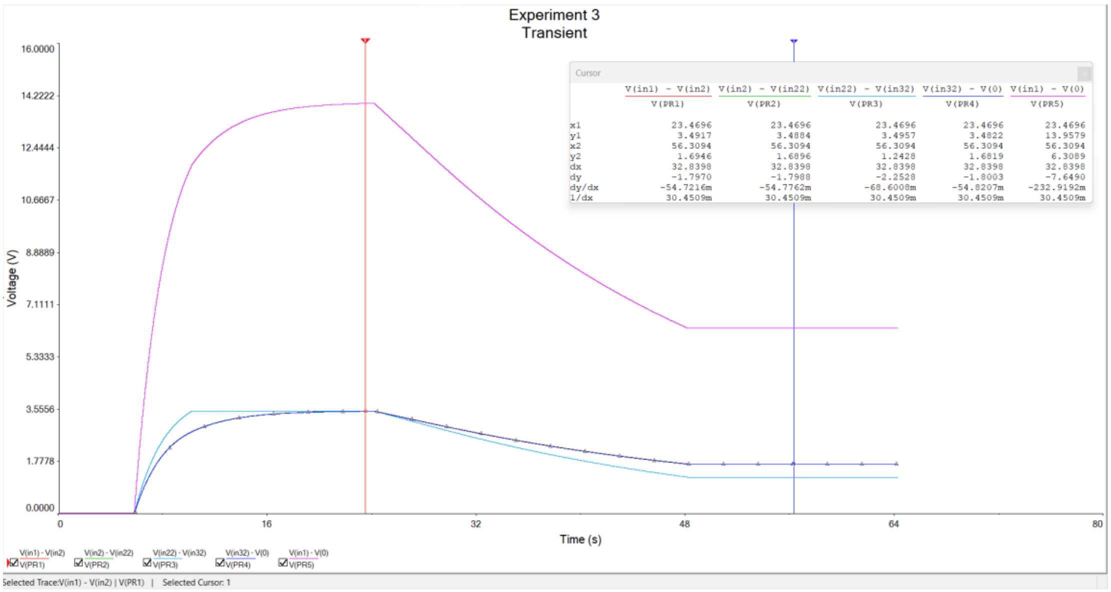


Figure 11 Charging and Discharging curve of the proposed design

From **Figure11** it is evident that the proposed design for cell balancing achieve the target of limiting the charge of weaker cell and balance all the cells connected In series for both charging and discharging state.

During discharge a unpredicted excess drop in the voltage of the weaker cell was observed, but the battery protection circuit ensured that the battery does not get completely drained. A further investigation is necessary to identify the reason behind excess voltage drop.

Advantages

- Achieve cell balancing with minimal/no losses.
- No waste of energy
- Easier to implement and low cost requirement
- Can instantly isolate cells from further charging
- Efficient use of the battery pack

Part C- Limitations and suggested improvements

Multi-sim Limitations

- The limitation associated with the modelling of chargeable batteries in the software due to which a capacitor had to be used as an alternative option, but the software does not take into consideration the transient effect caused due to imbalanced cell such as further degradation/impact on the batteries.
- The losses associated with the switching, resistance across the wire etc.
- Power loss associated using a resistor or MOSFETs which are dissipated in the form of heat.
- Unable to achieve voltage limiting for weaker cell during discharge despite the fact that the logic was satisfied for remaining cells
- Insufficient to memory to estimate the results for practical values

Practical Limitations

- The proposed design employs multiple switches and diode which may result in switching losses and reduced voltage.
- Since MOSFETs has its own specification, in case if the current flowing through them is higher than their rating it will result in bleeding of current into the cells increasing the voltage.
- A small amount of power loss can be predicted to be dissipated in the form of heat if a large amount of current is continuously flowing throw the MOSFETs for longer duration.

Improvements

As a part of improvement for the proposed design with minor additions an advanced cell balancing technique i.e. Dynamic cell balancing technique can be employed. In this approach for each cell SOC, SOH and the current rate will be constantly measured, using a microcontroller the current supplied to each can be adjusted considering the individual cells available capacity to maintain a constant charging and discharging rate. By this way a constant SOC can be maintained across different cell at any given point of time and not just when the battery is in idle state. (Lawson, 2012)

Conclusion

The cell balancing is necessary to achieve maximum battery pack performance which is limited by the weakest cell in the pack. The proposed design enables to utilise maximum capacity of the battery pack and achieve cell balancing without any energy loss in a very efficient manner. Also, a battery protection strategy is proposed to avoid overcharge and over discharge of the cells to ensure increased life span of the battery.

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